ARMY RESEARCH LABORATORY

Motion Sickness: A Brief Review and a Proposed Methodology for a Research Program

by Paul N. Rose

ARL-TN-0232 **November 2004**

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

DESTRUCTION NOTICE—Destroy this report when it is no longer needed. Do not return it to the originator.

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5425

ARL-TN-0232 **November 2004**

Motion Sickness: A Brief Review and a Proposed Methodology for a Research Program

Paul N. Rose
Human Research & Engineering Directorate, ARL

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
November 2004	Final	

4. TITLE AND SUBTITLE

Motion Sickness: A Brief Review and a Proposed Methodology for a Research Program

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Paul N. Rose (ARL)

5d. PROJECT NUMBER

61102A 74A

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Human Research & Engineering Directorate
Aberdeen Proving Ground, MD 21005-5425

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TN-0232

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Field studies in digitized command and control vehicles have found motion sickness to be a significant problem. It is difficult to isolate the cognitive effects of motion sickness in field studies because of the many other variables (e.g., vehicle vibration and noise and ambient temperature) that could potentially affect performance of cognitive tasks. A laboratory environment would allow researchers to isolate the effects of motion sickness on cognition. This report begins with a brief description of the field studies and the problems researchers encounter when they conduct them. After that, a theoretical account of motion sickness is described, followed by a description of the signs and symptoms of motion sickness. Finally, research that uses an optokinetic drum (a cylinder with black-and-white stripes painted on the inside wall) to produce motion sickness symptoms in human research participants is reviewed. Based on the research, the essential design elements for building an apparatus effective for studying motion sickness in the laboratory are given. Finally, a series of experiments is described and a broad list of research benefits is enumerated.

15. SUBJECT TERMS

cognitive performance; motion sickness; optokinetic drum

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Paul N. Rose
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL	25	19b. TELEPHONE NUMBER (*Include area code*) 410-278-5992

Contents

List of Figures

List of Tables

1. Introduction

For the last few years, the U.S. Army has been developing command and control vehicles (C2Vs) in which commanders would be able to manage battlefield operations. A number of field studies have been conducted under Army auspices to explain human-performance problems connected with C2Vs, especially problems that arise when operators engage in C2 functions while the C2V is moving. Because researchers envisioned the development and installation of digitized equipment in the C2V for management of the battlefield, subjects in the studies performed tasks displayed on computer monitors. Employing vehicles outfitted to simulate C2V interiors or actual C2V prototypes, researchers have found motion sickness to occur in some experimental subjects (Tauson, Doss, Rice, Tyrol, & Davidson, 1995; Cowings, Toscano, & DeRoshia, 1998), have found decrements in cognitive-task performance (Schipani, Bruno, Lattin, King, & Patton, 1998), or have found both effects (Cowings, Toscano, DeRoshia, & Tauson, 1999). This topic has more recently received increased research emphasis in anticipation of C2Vs for the Future Force.

Motion-related performance effects have more recently received increased research emphasis in anticipation of the adoption of enclosed vehicles for the interim and future forces. For the interim force, a baseline armored vehicle will be modified to serve a number of functions, including a mobile gun system, a reconnaissance vehicle, an infantry carrier, and a commander's vehicle. It is envisioned that many planning tasks conducted with digitized equipment will be undertaken while these vehicles are moving. It is important to understand the stressors operating on crew members in these vehicles.

The discovery that motion sickness (a class that includes other named sicknesses such as simulator sickness) is a common occurrence in enclosed vehicles is an important finding. Twenty to forty percent of the subjects from each of the Tauson et al. (1995) and Cowings et al. (1998) studies vomited, and Cowings et al. (1999) reported that all 24 of their subjects exhibited some motion sickness symptoms. Motion sickness has come to be recognized as an important variable in other high technology research domains as well. It has been documented, for example, that motion sickness occurs in individuals in ground (Lerman, Sadovski, Goldberg, Kedem, Peritz, & Pines, 1993) and aircraft simulators (Kennedy, Hettinger, & Lilienthal, 1990; Miller & Goodson, 1960) and in virtual environments (Regan & Price, 1994). Because simulators and (increasingly) virtual environments are used for training purposes, it is of some concern how motion sickness might hinder training or if it might induce the learning of coping methods that may result in suboptimal performance when individuals operate a vehicle in the real world.

A number of problems are associated with the conduct of field studies—the primary one being a lack of experimental control. For a study to be considered an experiment, at least two criteria

must be met: random assignment of subjects to treatment conditions and manipulation of an independent variable (Cook & Campbell, 1979). These criteria have been met in the Army field experiments. In addition, however, experimenters attempt to isolate the experimental participants from effects not of interest to the researchers. Doing so minimizes the variability within treatment conditions, leading to an increase in the power of the statistical test by decreasing the magnitude of the error term. In field settings, it is difficult to eliminate unwanted variables from a study. Using a C2V as the method to produce different levels of motion in an experiment probably introduces other variables as well. Noise might increase with speed because the engine must work harder to move the vehicle. Also, more rapid motion might lead to increases in vibration that further intensify noise. Other variables such as temperature might vary randomly or systematically during the course of the experiment. All these variables would be represented in the error term. A variable such as temperature could be controlled statistically by a technique such as analysis of covariance, but variables such as noise and vibration would be caused by and therefore correlated with motion. That is, high motion would produce high levels of noise and vibration, and low motion would produce low levels of these concomitant variables. These variables would increase variability in the dependent variable beyond that produced by motion sickness alone, and differences between the means of the dependent variable would be artifactually increased. Of course, all this assumes that motion sickness affects performance. If, in fact, there is no relationship between performance and motion sickness, the differences between the means of the dependent variable will be a function of noise and vibration, and the experimenter may falsely conclude that motion sickness is a significant variable.

In the present report, the author describes a research plan for studying motion sickness in a laboratory setting, which includes a brief synopsis of a number of studies. Briefly, the goals of the series of studies are to determine (a) which cognitive processes are affected by motion sickness, (b) how workload affects the course of motion sickness, and (c) whether motion sickness can be reduced by the projection of visual stimuli that are consonant with vestibular stimuli. Also described are experiments that will give additional insights into the nature of motion sickness.

Before we turn to laboratory methods for producing motion sickness, some subjects are discussed that will supply the context for a rationale for selecting the device and cognitive tasks. The following is not an all-inclusive review of motion sickness and all its ramifications. Only those topics relevant for the purpose of this report are covered.

2. Theoretical Account of Motion Sickness

Motion sickness is a relatively uncommon experience for most people riding in moving vehicles and usually occurs only in individuals riding in a form of transportation that is new to them. For

example, the advent of long-distance rail travel induced in early rail travelers a level of motion sickness greater than that experienced by rail passengers of today (Guignard & McCauley, 1990), partly because 19th century train passengers had no experience in seeing rapidly passing outside scenery. The necessity of novel motion has led most researchers to accept the sensory conflict theory, credited to Reason and Brand (1975), as an explanation of motion sickness. According to this theory, motion produces patterns of neural activity in the sensory systems (primarily the vestibular and visual sensory systems), which over repeated pairings, come to be expected to occur together. If novel motion environments give rise to pairs of neural sensory signals that previously have not been experienced together, motion sickness results. Motion sickness gradually abates as a new connection is made between the formerly unpaired sensory patterns.

The sensory conflict hypothesis has led researchers to consider various types of motion sickness, such as sea sickness and simulator sickness and previously inexplicable phenomena such as motion aftereffects, as related. For example, seasickness arises when the vestibular system detects accelerative linear bodily motion while the visual system detects none, as would occur in rough seas to passengers in a ship's cabin absent a porthole. In simulator sickness, on the other hand, just the opposite sensory pattern occurs: The visual system detects motion, which is conveyed by the projection system depicting flight, but the vestibular system detects little or no motion, because the mechanism that moves the simulator cockpit is unable to produce veridical flight motion or the simulator is a fixed base device and does not move.[1] Interestingly, experienced pilots are more susceptible than novices to simulator sickness (Miller & Goodson, 1960). In light of the sensory conflict hypothesis, one might expect such a finding, since, unlike novices, experienced pilots have developed a strong connection between the visual and vestibular sensations of actual flight and are therefore more likely to find the visual and vestibular patterns produced by a simulator to be conflicting.

Even though versions of the sensory conflict hypothesis have existed for more than 100 years to account for motion sickness,[2] an explanation of why sensory conflict would have such an effect awaited Treisman's (1977) account of the disorder. Treisman emphasized an organism's reliance on multiple sensory input (from the visual, vestibular, and proprioceptive systems) to coordinate all forms of bodily movement, including head, hand, and eye movement. These sources of information about bodily position and movement are continuously and simultaneously

---

[1] Some researchers object to characterizing simulator sickness as motion sickness for two reasons: many simulators do not move, so there is no real motion, and symptoms differ between motion and simulator sickness, primarily the likelihood of emesis (Casali, cited in Kennedy, Hettinger, & Lilienthal, 1990). This objection, however, misses the point. Motion sickness is the result of conflict between neural activity in sensory systems that detect motion. It is well documented that illusory, whole-body movement, known as vection, can be induced in individuals by visual stimuli alone (Previc & Donnelly, 1993; Telford & Frost, 1993; Telford, Spratley, & Frost, 1992), and other researchers have employed circular vection (induced by rotating a cylinder around stationary subjects) with pseudo-Coriolis stimulation to induce motion sickness in subjects (Dichgans & Brandt, 1973). It may be that emesis is less common and severe in simulators because the sensory conflict produced is less provocative.

[2] Most recent literature cites Reason and Brand (1975) as formally developing the sensory conflict theory (e.g., Yardley, 1992; Warwick-Evans, Symons, Fitch, & Burrows, 1999), yet Reason and Brand acknowledge that versions of the theory existed in the late 19th century.

monitored, and the relationships between them, which are learned through experience, must be in accordance in order for coordinated movement to be possible. In the past, when humans' sole means of transport was by foot, the only way to disrupt the correlation between sensory input was through ingestion of toxins that affect neural systems. Those organisms that vomited in response to toxin-induced sensory conflict eliminated neurotoxins sooner than those that relied on slower mechanisms. Toxin-produced sensory conflict would have been an important evolutionary development and would have increased the survival of the organism over other members of its species. In other words, vomiting because of conflicting sensory input had survival value for the organism, and this trait was selected by the environment. We can artificially produce sensory conflict today by subjecting individuals to motion stimuli that are discordant because they have never been experienced together. According to Treisman then, "motion sickness is an adaptive response evoked by an inappropriate stimulus" (p. 495). Treisman's account became known as the evolutionary hypothesis of motion sickness.

The sensory conflict theory can be used to account for why motion sickness occurs in the C2V. In the past, subjects have experienced riding over rough terrain while viewing the surrounding scenery, which resulted in vestibular and visual sensations of movement. In the C2V, subjects ride in an enclosed compartment, which results in vestibular stimulation suggesting motion and incongruent visual stimulation indicating stillness. This discrepant sensory information results in motion sickness.

A general conclusion of the sensory conflict hypothesis is that new technology that stimulates incongruent sensory information will result in motion sickness. Simulators, virtual environments, and vehicles operated via television monitors fall into this category. There have even been reports in the popular press of motion sickness arising in unexpected venues. There were, for example, reports in 1999 that viewers of the film "The Blair Witch Project" became sick, with one theater in Atlanta reporting that at each showing of the film at least one member of the audience vomited (Eldredge, 1999; Mays, 1999). This was attributed to the continual movement of the camera during filming. Increased incidents of motion sickness have also been reported in sport utility vehicles equipped with TVs (Furchgott, 2000), suggesting that simply diverting one's eyes to a TV changes visual sensations of movement in a vehicle that is not enclosed.

3. Signs and Symptoms of Motion Sickness

The complete list of clinical signs and symptoms for motion sickness is somewhat broad. The cardinal symptoms are pallor, cold sweating, nausea, and vomiting, and secondary symptoms include salivation, drowsiness, retching, yawning, burping, dizziness, and headache (Graybiel, Wood, Miller, & Cramer, 1968). In addition to these clinical symptoms, Graybiel et al. (1965)

have identified changes in biochemical functions. The syndrome-like nature of motion sickness leads to questions about how the nature of the malady changes as these symptoms develop and how its severity affects cognitive processes. Obviously, vomiting would affect a sufferer's performance of any task, cognitive or noncognitive. Less certain are answers to questions concerning the cognitive effects of mild nausea or drowsiness. Would the pattern of cognitive effects for nausea be different from the pattern resulting from drowsiness?

Graybiel (1969), summarizing results from studies of groups of participants living in a slowly rotating room (see Graybiel, 1969, for a brief account; Graybiel et al., 1965, for a more extensive description), divided motion sickness symptoms into two categories: one containing symptoms such as nystagmus and dizziness directly associated with disturbances of the vestibular system, and the other containing symptoms not directly associated with the vestibular system. The second category was quite broad and included not only symptoms by which motion sickness is typified (pallor, nausea, and vomiting) but also secondary clinical symptoms, such as drowsiness, and nonclinical symptoms, such as changes in biochemical functioning. Graybiel held that there was a connection (which he termed a "facultative link") between the vestibular and nonvestibular systems mediating their respective symptoms, and that it was necessary for the vestibular system to be perturbed before the nonvestibular system could be affected.

In a second paper, Graybiel and Knepton (1976) focused on drowsiness, noting that although it often accompanied other symptoms of motion sickness, it could also appear in the absence of the other symptoms or after individuals had adapted to the motion and the nauseous symptoms disappeared. Sufferers reported difficulty recalling information and exhibited a lack of interest in engaging in mental or physical tasks or of interacting with other participants in the study; experimenters and observers noted a link between subjects' drowsiness and increases in errors. Although Graybiel and Knepton used the term drowsiness, it may be more accurate to employ the term "lethargy" to designate this effect. Even several hours of sleep did not relieve it, and anti-motion sickness medications, which themselves have mild narcoleptic effects, nevertheless mitigated motion-induced lethargic effects, resulting in reports of improved performance of tasks by individuals who ingested anti-motion sickness medications. As a result of the independent and profound effects of motion-induced lethargy, Graybiel and Knepton coined the phrase *sopite syndrome* to refer to it. Because of the independence of the sopite syndrome from other motion sickness symptoms, it may be possible to adopt methods to reduce nausea and vomiting, but if we neglect to take lethargy into consideration, there will still be decrements in performance.

4. Other Variables Affecting Performance

The wide range of signs and symptoms characterizing motion sickness presents a problem for research done in natural settings because other environmental stressors may cause a subset of

them. Potential confounding variables are noise, heat, and vibration. Vibration is a particularly difficult variable to deal with since it may vary with motion. Vibration affects the human body directly by physiological and biomechanical means and usually results in brief elevations in circulatory and respiratory rates, increased muscle activity to counteract the vibration, and, if the vibration is extensive, injury of the skeleton and joints (Kjellberg & Wikström, 1985). In addition, vibration may initially increase arousal, leading to improved performance, only to be followed by fatigue and deteriorating performance if a person resists vibration through muscle contractions. Furthermore, vibration has been shown to affect cognitive performance even in experiments that control its fatiguing effects. Sherwood and Griffin (1990) presented vertical whole-body vibration to participants who sat in a chair (16 Hz sinusoidal motion at 1.0, 1.6, and 2.5 m/s^2 root mean square [rms]). They attempted to control for fatigue and decrements in motivation by keeping sessions short and by paying participants. They also controlled for task-disrupting head and hand movements by employing large visual stimuli and hand-held buttons, further making fatigue less of a confound since participants did not have to resist the motion to see or respond to stimuli. They found that memory-scanning speed deteriorated, and in a later study adopting similar controls (Sherwood & Griffin, 1992), they found that list learning was impeded by vertical, sinusoidal, whole-body vibration (16 Hz, 2.0 m/s^2 rms) similar to that produced by rotary wing aircraft.

5. The Use of a Rotating Drum to Induce Motion Sickness

From the brief review just given, it is obvious that discordant visual and vestibular stimuli result in motion sickness. One of the least expensive methods often used to create this conflict between sensory modalities relies on an apparatus called an optokinetic drum, which consists of a cylinder with (usually) black-and-white vertical stripes painted on the inner surface. The cylinder is slowly rotated around an experimental participant whose head is situated at the cylinder's axis. Often, the apparatus is constructed so that the chair can spin independently of the cylinder. Dichgans and Brandt (1973), for example, employed such an apparatus to study the similarities between conditions in which the chair, cylinder, or both rotated. They also added a variable to their study, Coriolis stimulation, in which participants tilted their heads forward and backward and side to side. This motion causes additional vestibular sensations of motion in the semi-circular canals, significantly increasing the magnitude of motion sickness. By employing these three variables in combination, Dichgans and Brandt were able to induce more than mild to moderate motion sickness symptoms in their participants. For example, when Coriolis motion took place with both the chair and drum rotating in the same direction but at different speeds, several subjects vomited after only one set of head tilts.

The experiments that are planned and described in this report require only the cylinder to rotate, primarily because the author is interested in the effects of low to moderate levels of motion

sickness on cognition. The papers listed in table 1 give an idea of the effectiveness of using a cylinder as the sole means of generating motion sickness. These studies help set the dimensions of the cylinder, the optimum rate of rotation, and length of time required to produce motion sickness, and the number of subjects needed in order to obtain significant results.

Table 1. Time in cylinder, motion sickness, and sample size.

Study	Time in Cylinder (minutes)	Mean Motion Sickness Score	Incidence of Motion Sickness (percent)	N
Hu, Willoughby et al. 1996	10	5.8		51
Hu, Glasser et al., 1996	12	6.4	45[e]	49
Stern et al., 1990	12	7.9	53	15
Hu, Stern et al., 1989	15	6.8	53[n]	15
Hu, Davis et al., 1997	16	7.8		20
Uijtdehaage et al., 1992	16	3.7		40
Hu and Hui, 1997	16	9.9	68	40
Zhao and Stern, 1999	16	6.3	45 [e]	31
Feinle et al., 1995	30	11.5[m]	75 [e]	12

Motion sickness score assessed by the Pensacola Diagnosis Index (PDI). Some of the PDI scores were estimated by the author from figures that show data. A PDI designated with an [m] is a median. The incidence of motion sickness was reported by authors of the study or estimated by the author of this report, based on data supplied in the papers. Estimates designated by an [e] are percentage of participants with PDI scores ≥ 6; estimates designated by an [n] are percentage of participants experiencing nausea.

All the studies employed the Pensacola Diagnostic Index (PDI) (Graybiel et al., 1968) to assess degree of motion sickness, and all used cylinders with either 5.7-degree black and 9.3-degree white stripes or with 7.5-degree black stripes and white stripes. (Feinle et al. do not report the visual angle subtended by their stripes.) The author estimated the mean motion sickness scores reported in table 1 by calculating the means from tabled data or by estimating the mean from figures in the original papers. Zhao and Stern (1999) report that with PDI scores above 6, participants exhibit obvious motion sickness symptoms such as dizziness, sweating, and headache; the author therefore used a PDI score of 6 as an index to estimate the percentage of participants experiencing motion sickness, shown in the next-to-the-last column of table 1. These estimates are indicated in the table with a lower case letter *e* as a superscript. In the Hu et al. (1989) paper, the number of participants experiencing nausea was reported by the authors, and this percentage is indicated with an *n* superscript. All other estimates in the column were explicitly reported by the papers' authors as percentages or frequencies of participants who became sick, with sick defined as, for example, the presence of stomach discomfort. Three of the studies did not present enough information for the author to calculate the percentage of subjects who became motion sick, and therefore, only the mean motion sickness score is given. The final column of table 1 indicates the sample sizes upon which PDIs and motion sickness incidences are based. Sample sizes larger than 20 were actually based on pooling scores from two or more groups. Hu, Glasser, et al. (1996), for example, employed three groups, each with 16 or 17 participants; Uijtdehaage et al. (1992) and Hu and Hui (1997) each had two 20-participant groups. Only Hu, Willoughby, et al. (1996) employed groups larger than 20 members (one was 23, the

other 28). In short, most studies used groups consisting of 15 to 20 participants, yet were able to obtain significant differences between groups or within groups across blocks of trials.

This information gives guidance in regard to the design of the optokinetic drum. Hu, Stern, Vasey, and Koch (1989) showed that motion sickness was maximized when a drum rotated at a rate of 60 degrees per second (10 revolutions per minute [rpm]), and Hu, Davis et al. (1997) showed that black-and-white stripes each with a visual angle of 7.5 degrees are most effective at producing motion sickness in individuals. Another generalization that can be distilled from these studies is that motion sickness can be produced with sessions of 15 minutes' duration and that about 50% of experimental participants exhibit mild to moderate motion sickness. Finally, studies with groups of 15 to 20 subjects are sufficient to obtain significant results.

For the purpose of the planned studies described in this report, the optokinetic drum should consist of a cylinder with 48 black-and-white vertical stripes, each subtending a visual angle of 7.5 degrees. Motion sickness will be induced in participants by rotating the cylinder at 10 rpm. Participants will view the inner wall of the cylinder while sitting in a chair. About 1/3 of the cylinder will be above and 2/3 below eye level. A computer keyboard will be mounted directly above the participant's lap. A flat-panel display will be mounted above the keyboard at about a 45-degree angle, upon which task-relevant visual stimuli can be presented. Auditory tasks will be presented over earphones. Participants will perform tasks by using the computer keyboard. The computer will control cylinder speed and presentation of the auditory and visual tasks.

6. Research

This section outlines some potential experiments that could be performed with the optokinetic drum. The objective is to describe a programmatic series of studies employing this tool.

The research described falls roughly into three categories. In the first, a series of experiments is described that assesses the effects of motion sickness on simple and complex cognitive tasks. One purpose is to establish that motion sickness can be produced by the optokinetic drum while participants engage in simple visual tasks presented on a computer monitor. Stern, Hu, Anderson, Leibowitz, and Koch (1990) have shown that fixation and restrictions of the visual field reduce the nausogenitive effectiveness of the optokinetic drum. In the second category, experiments of motion sickness on more test-like cognitive tasks will be described. Experiments from both categories will help select those cognitive tasks that are most sensitive to motion sickness-induced cognitive decrements. Finally, an attempt will be made to create visual stimuli that can be projected on the rotating cylinder wall, which will provide visual cues that are in harmony with the sensations of the vestibular system. It is hypothesized that harmonious visual stimuli would reduce the incidence and magnitude of motion sickness. Experiments attempting to address this question fall into the third category.

6.1 Category 1: Can motion sickness be produced when subjects are involved in simple tasks, and is performance of the tasks affected by motion sickness?

Stern et al. (1990) and Dichgans and Brandt (1973) have shown that restriction of the field of view and fixation on a black cross between the participant and wall of the optokinetic drum reduces the nausogenic effectiveness of the drum. Since participants in the current experiment will have to look at objects on a computer monitor (which itself will obscure some of the view of the rotating drum), it is necessary to ensure that motion sickness can actually be produced by the optokinetic drum.

An experiment designed to answer this question can employ a variety of tasks: a vigilance task, a Sternberg (1966) memory-scanning task, a memorization task, and a complex task. The experimental matrix for a typical task appears in table 2. There are two treatment conditions. In the experimental condition, participants perform a task for six blocks of trials while the cylinder is rotating at 60 degrees per second (10 rpm); the control participants sit in the cylinder while they perform the task, but the cylinder is stationary. After completion of this phase of the experiment, both groups will continue to perform the task for an additional six blocks, as shown in table 2. This will provide an opportunity to study motion aftereffects. At the end of each block of trials, a motion sickness questionnaire will appear on the computer monitor, which will allow participants to record their motion sickness level.

Table 2. General experimental matrix for experiment 1.

Group	Experimental Control	First Half-Block of Trials						Last Half-Block of Trials					
		1	2	3	4	5	6	7	8	9	10	11	12
	Experimental	Motion at 10 rpm						No motion					
	Control	No motion						No motion					

These three tasks can be presented visually or auditorily. For the vigilance task, for example, a small white disk can be displayed on the computer monitor. Every 2 seconds, the brightness can be increase for about 0.1 second. On about 1/3 of the trials, the increase in brightness will be above the standard increase. The participant will press one button when the low-level flash occurs and another button when the brighter flash occurs. The dependent variables will be the signal detection metrics β and d'. This task can be easily converted to an auditory task by substitution of a 500-Hz tone for the light. In comparing performance on visual and auditory analogues of the same task, we can determine if a computer monitor will reduce the effectiveness of the optokinetic drum.

A Sternberg task would allow assessment of the effects of motion sickness on memory scanning and would also follow the design shown in table 2. In a Sternberg task, participants view letters presented one at a time after they have memorized a short list ranging from one to six letters. They indicate whether a presented letter was a member of the list by pressing a button. From such an experiment, it can be determined if the rate at which the participants scan the list is affected by motion sickness.

The memorization task is modeled after one used by Sherwood and Griffin (1992). They displayed one at a time a list of names to participants who were told that the names represented members of two sports teams and that the task was to learn which individuals were on which team. Each time a name appeared on the monitor, the participant indicated whether the person was on team A or B by pressing buttons. The participant received feedback about the accuracy of his or her decision. Over repeated presentation of the list of names, the participants gradually learned who was on which team. The dependent variable was the number of correctly assigned names. Employing this task would allow one to assess the effect of motion sickness on learning new material. Both this task and the Sternberg task can be presented auditorily as well as visually.

A final task is a complex task consisting of three subtasks. Figure 1 shows a circle with wings displayed on a computer monitor. In the first subtask, the wings will tilt 30 degrees, first clockwise then counterclockwise, giving the appearance of a seesaw; the participants will attempt to keep the wings horizontal by manipulating a joystick. In the second subtask, letters will appear one at a time in the circle, and the participants will indicate whether each letter is a member of a previously memorized list of letters (i.e., they will engage in a Sternberg task). The final subtask is a peripheral detection task. Occasionally, a disk will appear in one of the corners of the computer monitor. Participants will indicate when this happens by pressing a button. Participants will perform all three subtasks simultaneously. Obviously, the complex task has no auditory analogue.

Again, table 2 delineates the experimental matrix for all these tasks.

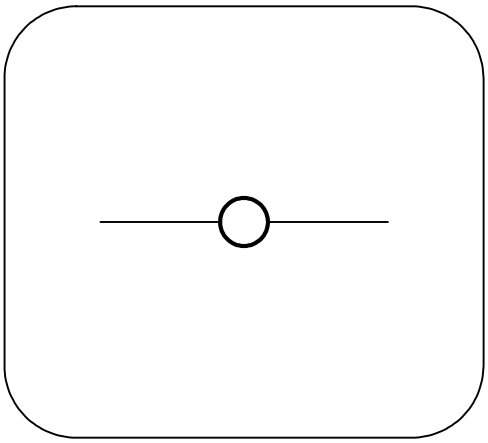

Figure 1. Complex task.

6.2 Category 2: Are more complex measures of cognition more sensitive to the effects of motion sickness?

Often, more test-like measures of cognition are used to measure performance decrements resulting from environmental stressors. Usually, several tests, each of which measures a different cognitive ability, are collected together to form a test battery. The tests in the battery

are administered in a fixed sequence to all subjects across all treatment conditions. Several limitations result when this procedure is followed. First, participants may engage in greater effort when taking a test that measures a cognitive ability actually affected by motion sickness, thus allowing them to recover and conserve cognitive potency during less taxing tests. In addition, stressors usually affect performance gradually over time. This would mean that a test in a battery given at the end of a session would be more affected by the stressor than one given at the beginning, causing the investigators to conclude that only some cognitive abilities (i.e., those measured by test at the end of the battery) are affected by the stress. Finally, researchers often put their subjects through an extended period of training on the tests in a non-aversive environment, for the purposes of reducing variability of scores on each test and eliminating improvement in test scores as a confounding variable in the study (i.e., training to achieve an asymptote). Of course, training is usually prescribed for a wide variety of jobs so that individuals will able to perform a task efficiently in a wide variety of aversive situations. Therefore, overtraining experimental participants on a test might be expected to enable participants to effectively perform the test in a stressful environment, making it less likely for the researcher to find a significant relationship between the stressor and performance.

Using the experimental design shown in table 2, one could study the effects of motion sickness on a variety of cognitive tests, one test at a time. A test battery that more effectively measures cognitive performance in nausogenic environments could then be constructed.

6.3 Category 3: Can stimuli be projected on the wall of the cylinder to reduce the nausogenic effects of the rotating cylinder?

Experiments 1 and 2 should reveal cognitive tasks that are especially sensitive to the effects of motion sickness. The most sensitive would be used in experiment 3 to determine if there is a stimulus pattern that can be projected onto the wall of the rotating cylinder, which provides visual cues that are consonant with participants' vestibular sensations of no motion. Recall that according to the sensory conflict hypothesis, motion sickness is attributable to pairs of dissonant sensory stimulations that result from immersion in a novel environment. In the optokinetic drum, the visual system registers motion while the vestibular system detects no motion. Projecting visual stimuli that reinforce vestibular sensation of no motion may reduce motion sickness. This would result in lower scores on a motion sickness questionnaire and better performance of the cognitive task. Findings could be transferred to the field for evaluation.

7. Additional Experiments

The cylinder apparatus could be modified to conduct additional experiments. A chair that rotates independently of the cylinder, similar to that of Dichgans and Brandt (1973), could be added to

expand experimental capabilities. Rotating the cylinder and holding the chair stationary is an analogue of the type of motion experienced in a fixed base simulator, in which motion is experienced visually but not vestibularly. Rotating the chair and holding the cylinder stationary is an analogue of riding inside an enclosed moving vehicle. These two conditions are interesting because the rate of visual change can be held constant and the vestibular stimulation manipulated independently. That is, the chair or cylinder can be rotated at 10 rpm, resulting in the stripes on the cylinder wall giving equivalent visual indications of motion. The vestibular system, however, detects motion only when the chair rotates. It would be interesting to compare these two conditions.

In a third condition, the chair could move counterclockwise at 5 rpm and the cylinder clockwise at 5 rpm. Visually, then, the motion of the stripes would be a function of the combined chair and cylinder motion. The visual system would register a stripe motion of 10 rpm, but the vestibular system would detect a slower degree of motion. This combination of effects would be an analogue of controlling a robotic vehicle from inside a moving vehicle. Researchers could then explore the nausogenic-inducing abilities of these three environments.

8. Benefits

The benefits of this proposed research are

1. Conducting motion sickness studies in the laboratory allows numerous variables to be examined less expensively than can be achieved in a series of field studies.
2. Effects of variables of interest can be brought into the laboratory and can be isolated from the effects of variables not of interest.
3. Many researchers are using simulators for training and for conducting research. In a personal conversation with researchers who use a driving simulator in their work, the author asked if experimental participants ever became motion sick. One researcher indicated that some participants did report being made uneasy by the simulated motions and that one became sufficiently sick to be released from the study. No mention of this problem appeared in any of these researchers' reports. Research on the cognitive effects of motion sickness might reveal that, for instance, learning is impaired or performance is hindered in simulators. Such findings would have important implications for training and research in simulators.
4. The more complex apparatus described previously, in which the chair and cylinder rotate separately, would allow comparison of a variety of environments, simulators, driving, and robotic control of other ground vehicles.

5. It is difficult for Army researchers to study stress. Some stressors such as lack of sleep take hours to show their effects, and others such as noise must be administered at low levels to avoid permanent hearing damage. The optokinetic drum can be used to create stress in a short period of time (15 minutes). Motion sickness has been compared to the effects experienced when neurotoxins are ingested. The optokinetic drum, then, can become a standard laboratory method to induce stress in the laboratory.
6. Over the course of the experiments described, the relationship between scores on the motion sickness questionnaire (and the factors comprising the overall score) and performance of the cognitive tasks and tests can be determined. The questionnaires can then be administered to individuals in novel environments, and the scores can in turn be used to make predictions about human performance in those environments.
7. The research strategy described in this report not only allows research on applied problems but also provides the opportunity for basic research on the effects of motion sickness.

9. References

Cook, T. S.; Campbell, D. T. *Quasi-Experimentation: Design and analysis issues;* New York: Houghton Mifflin Co. (1979).

Cowings, P. S.; Toscano, W. B.; DeRoshia, C. *Evaluation of the frequency and severity of motion sickness incidences in personnel within the command and control vehicle (C2V)*; Report No. NAS115112221; National Aeronautics and Space Administration, Ames Research Center: Moffett Field, CA, (1998).

Cowings, P. S.; Toscano, W. B.; DeRoshia, C.; Tauson, R. A. *The effects of the command and control vehicle (C2V) operational environment on soldier health and performance*; ARL-MR-468; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, (1999).

Dichgans, J.; Brandt, T. Optokinetic motion sickness and pseudo-coriolis effects induced by moving visual stimuli. *Acta Oto-laryngologica* **1973**, *76*, 339–348.

Eldredge, R. L. 'Blair' a horror for cleanup crews. *Atlanta Constitution*, August 10, 1999. p. D2.

Feinle, C.; Grundy, D.; Read, N. W. Fat increases vection-induced nausea independent of changes in gastric emptying. *Physiology and Behavior* **1995**, *58*, 1159–1165.

Furchgott, R. Where the TV room meets the road. *The New York Times*, June 15, 2000.

Graybiel, A. Structural elements in the concept of motion sickness. *Aerospace Medicine* **1969***, 40,* 351–367.

Graybiel, A.; Kennedy, R. S.; Knoblock, E. C.; Guedry, F. E.; Mertz, W.; McLeod, M. E.; Colehour, J. K.; Miller, E. F.; Fregly, A. R. Effects of exposure to a rotating environment (10 rmp) on four aviators for a period of twelve days. *Aerospace Medicine* **1965***, 36,* 733-754.

Graybiel, A.; Knepton, J. Sopite syndrome: A sometimes sole manifestation of motion sickness. *Aviation, Space, and Environmental Medicine* **1976***, 47,* 873–882.

Graybiel, A.; Wood, C. D.; Miller, E. F.; Cramer, D. B. Diagnostic criteria for grading the severity of acute motion sickness. *Aerospace Medicine* **1968***, 39,* 453-455.

Guignard, J. C.; McCauley, M. E. *The accelerative stimulus for motion sickness*; In G. H. Crampton (Ed.) Motion and space sickness (pp. 123–152). Boca Raton, FL: CRC Press, (1990).

Hu, S.; Davis, M. S.; Klose, A. H.; Zabinsky, E. M.; Meux, S. O.; Jacobsen, H. A.; Westfall, J. M.; Grubber, M. B. Effects of spatial frequency of vertically striped rotating drum on vection-induced motion sickness. *Aviation, Space, and Environmental Medicine* **1997***, 68*, 306–311.

Hu, S.; Glaser, K. M.; Hoffman, T. S.; Stanton, T. M.; Gruber, M. B. Motion sickness susceptibility to optokinetic rotation correlates to past history of motion sickness. *Aviation, Space, & Environmental Medicine* **1996**, 67, 320–324.

Hu, S.; Hui, L. Adaptation to optokinetic rotation-induced motion sickness without experiencing nausea. *Perceptual and Motor Skills* **1997**, *84*, 1235–1240.

Hu, S.; Stern, R. M.; Vasey, M. W.; Koch, K. L. Motion sickness and gastric myoelectric activity as a function of speed of rotation of a circular vection drum. *Aviation, Space, & Environmental Medicine* **1989**, *60*, 411–414.

Hu, S.; Willoughby, L. M.; Lagomarsino, J. J.; Jaeger, H. A. Optokinetic rotation-induced taste aversion correlate with over-all symptoms of motion sickness in humans. *Perceptual and Motor Skills* **1996**, *82*, 859–864.

Kjellberg, A.; Wikström, B-O. Whole-body vibration: Exposure time and acute effects–a review. *Ergonomics* **1985***, 28,* 535–544.

Kennedy, R. S.; Hettinger, L. J.; Lilienthal, M. G. Simulator sickness. In G. M. Crampton (Ed.), *Motion and space sickness*, 1990, 317–342.

Lerman, U.; Sadovski, G.; Goldberg, E.; Kedem, R.; Peritz, E.; Pines, A. Correlates of military tank simulator sickness. *Aviation, Space, and Environmental Medicine* **1993**, *64*, 619–622.

Mays, P. J. 'Blair Witch' movie making fans queasy. *Atlanta Constitution*, August 13, 1999, p. C7.

Miller, J. W.; Goodson, J. E. Motion sickness in a helicopter simulator. *Aerospace Medicine* **1960***, 31*, 204–212.

Previc, F. H.; Donnelly, M. The effects of visual depth and eccentricity on manual bias, induced motion, and vection. *Perception* **1993***, 22,* 929–945.

Reason, J. T.; Brand, J. J. *Motion sickness.* New York: Academic Press, 1975.

Regan, E. C.; Price, K. R. The frequency of occurrence and severity of side-effects of immersion virtual reality. *Aviation, Space, and Environmental Medicine* **1994**, *65*, 527–530.

Schipani, S. P.; Bruno, R. S.; Lattin, M. A.; King, B. M.; Patton, D. J. *Quantification of cognitive process degradation while mobile, attributable to the environmental stressors endurance, vibration, and noise*; ARL-TR-1603; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 1998.

Sherwood, N.; Griffin, M. J. Effects of whole-body vibration on short-term memory. *Aviation, Space, and Environmental Medicine* **1990***, 61,* 1092–1097.

Sherwood, N.; Griffin, M. J. Evidence of impaired learning during whole-body vibration. *Journal of Sound and Vibration* **1992**, *152*, 219–225.

Stern, R. M.; Hu, S.; Anderson, R. B.; Leibowitz, H. W.; Koch, K. L. The effects of fixation and restricted visual field on vection-induced motion sickness. *Aviation, Space, & Environmental Medicine* **1990**, *61*, 712–715.

Sternberg, S. High-speed scanning in human memory. *Science* **1966***, 153* (3736), 652–654.

Tauson, R. A.; Doss, W.; Rice, D. J.; Tyrol, D. E.; Davidson, D. *The effect of vehicle noise and vibration (caused by moving operations) on cognitive performance in the commend and control vehicle*; ARL-MR-279; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 1995.

Telford, L.; Frost, B. J. Factors affecting the onset and magnitude of linear vection. *Perception & Psychophysics* **1993***, 53,* 682–692.

Telford, L.; Spratley, J.; Frost, B. J. Linear vection in the central visual field facilitated by kinetic depth cues. *Perception* **1992***, 21,* 337–349.

Treisman, M. Motion sickness: An evolutionary hypothesis. *Science* **1977***, 197* (4302), 493–495.

Uijtdehaage, S. H. J.; Stern, R. M.; Koch, K. L. Effects of eating on vection-induced motion sickness, cardiac vagal tone, and gastric myoelectric activity. *Psychophysiology* **1992**, *29*, 193–201.

Warwick-Evans, L. A.; Symons, J.; Fitch, T.; Burrows, L. Evaluating sensory conflict and postural instability. Theories of motion sickness. *Brain Research Bulletin* **1999**, 47, 465–469.

Yardley, L. Motion sickness and perception: A reappraisal of the sensory conflict approach. *British Journal of Psychology* **1992***, 83,* 449–471.

Zhao, L.; Stern, R. M. Absence of habituation to repeated exposures to a rotating optokinetic drum with brief intersession intervals. Perceptual & Motor Skills **1999**, *89* (3, Pt 1), 778–782.

NO. OF COPIES ORGANIZATION

* ADMINISTRATOR
DEFENSE TECHNICAL INFO CTR
ATTN DTIC OCA
8725 JOHN J KINGMAN RD STE 0944
FT BELVOIR VA 22060-6218
*pdf file only

1 DIRECTOR
US ARMY RSCH LABORATORY
ATTN IMNE AD IM DR MAIL & REC MGMT
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 DIRECTOR
US ARMY RSCH LABORATORY
ATTN AMSRD ARL CI OK TECH LIB
2800 POWDER MILL RD
ADELPHI MD 20783-1197

1 ARL HRED AVNC FLD ELMT
ATTN AMSRD ARL HR MJ D DURBIN
BLDG 4506 (DCD) RM 107
FT RUCKER AL 36362-5000

1 ARL HRED AMCOM AUN FLD ELMT
ATTN AMSRD ARL HR MI
BLDG 5464 RM 202 J MINNINGER
REDSTONE ARSENAL AL 35898-7290

1 ARL HRED AMCOM MSL FLD ELMT
ATTN AMSRD ARL HR MO T COOK
BLDG 5400 RM C242
REDSTONE ARS AL 35898-7290

1 ARL HRED USAADASCH FLD ELMT
ATTN AMSRD ARL HR ME A MARES
ATTN ATSA CD
5800 CARTER ROAD
FORT BLISS TX 79916-3802

1 ARL HRED ARDEC FLD ELMT
ATTN AMSRD ARL HR MG R SPINE
BUILDING 333
PICATINNY ARSENAL NJ 07806-5000

1 ARL HRED ARMC FLD ELMT
ATTN AMSRD ARL HR MH C BURNS
BLDG 1002 ROOM 117
1ST CAVALRY REGIMENT RD
FT KNOX KY 40121

1 ARL HRED CECOM FLD ELMT
ATTN AMSRD ARL HR ML J MARTIN
MYER CENTER RM 2D311
FT MONMOUTH NJ 07703-5630

NO. OF COPIES ORGANIZATION

1 ARL HRED FT BELVOIR FLD ELMT
ATTN AMSRD ARL HR MK J REINHART
10125 KINGMAN RD
FORT BELVOIR VA 22060-5828

1 ARL HRED FT HOOD FLD ELMT
ATTN AMSRD ARL HR S MIDDLEBROOKS
MV HQ USAOTC
91012 STATION AVE ROOM 111
FT HOOD TX 76544-5073

1 ARL HRED FT HUACHUCA FLD ELMT
ATTN AMSRD ARL HR MY M BARNES
2520 HEALY AVE STE 1172 BLDG 51005
FT HUACHUCA AZ 85613-7069

1 ARL HRED FLW FLD ELMT
ATTN AMSRD ARL HR MZ A DAVISON
320 MANSCEN LOOP STE 166
FT LEONARD WOOD MO 65473-8929

1 ARL HRED NATICK FLD ELMT
ATTN AMSRD ARL HR MQ M R FLETCHER
NATICK SOLDIER CTR BLDG 3
AMSRD ARL NSC SE E
NATICK MA 01760-5020

1 ARL HRED SC&FG FLD ELMT
ATTN AMSRD ARL HR MS C MANASCO
SIGNAL TOWERS RM 303A
FORT GORDON GA 30905-5233

1 ARL HRED STRICOM FLD ELMT
ATTN AMSRD ARL HR MT C CHEN
12350 RESEARCH PARKWAY
ORLANDO FL 32826-3276

1 ARL HRED TACOM FLD ELMT
ATTN AMSRD ARL HR MU M SINGAPORE
6501 E 11 MILE RD MAIL STOP 284
BLDG 200A 2ND FL RM 2104
WARREN MI 48397-5000

1 ARL HRED USAFAS FLD ELMT
ATTN AMSRD ARL HR MF C HERNANDEZ
BLDG 3040 RM 220
FORT SILL OK 73503-5600

1 ARL HRED USAIC FLD ELMT
ATTN AMSRD ARL HR MW E REDDEN
BLDG 4 ROOM 332
FT BENNING GA 31905-5400

NO. OF
COPIES ORGANIZATION

1 ARL HRED USASOC FLD ELMT
ATTN AMSRD ARL HR MN R SPENCER
DCSFDI HF
HQ USASOC BLDG E2929
FORT BRAGG NC 28310-5000

1 ARL HRED FT LEAVENWORTH FLD ELMT
ATTN AMSRD ARL HR MP
D UNGVARSKY
BATTLE CMD BATTLE LAB
415 SHERMAN AVE UNIT 3
FT LEAVENWORTH KS 66027-2326

1 ARL HRED AMEDD FLD ELMT
ATTN AMSRD ARL HR MM V RICE
BLDG 4011 RM 217
1750 GREELEY RD
FT SAM HOUSTON TX 78234-5094

1 ARL HRED SPO
ATTN AMSRD ARL HR M M STRUB
6359 WALKER LAND STE 100
ALEXANDRIA VA 22310

1 ARL HRED JFCOM FLD ELMT
ATTN AMSRD ARL HR MJF D BARNETTE
JFCOM JOINT EXPERIMENTATION J9
JOINT FUTURES LAB
115 LAKEVIEW PKWY STE B
SUFFOLK VA 23535

1 DIRECTOR
UNIT OF ACTION MANEUVER BATTLE LAB
ATTN ATZK UA
BLDG 1101
FORT KNOX KY 40121

ABERDEEN PROVING GROUND

1 DIRECTOR
US ARMY RSCH LABORATORY
ATTN AMSRD ARL CI OK TP (TECH LIB)
BLDG 4600

1 DIRECTOR
US ARMY RSCH LABORATORY
ATTN AMSRD ARL CI OK TP S FOPPIANO
BLDG 459

1 DIRECTOR
US ARMY RSCH LABORATORY
ATTN AMSRD ARL HR MB
F PARAGALLO
BLDG 459

NO. OF
COPIES ORGANIZATION

1 DIRECTOR
US ARMY RSCH LABORATORY
ECBC FLD ELMT
ATTN AMSRD ARL HR M
BLDG 459